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METHOD FOR ESTIMATING THE REMAINING CAPACITY OF THE CARBON DIOXIDE SCRUBBER IN THE HYPERBARIC OXYGEN TREATMENT PACK

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ABSTRACT

The Hyperbaric Oxygen Treatment Pack (HOTP), a part of the Submarine Rescue and Decompression System is essentially a closed-circuit breathing apparatus. Therefore, it has a CO_2 absorber with a limited, often unpredictable lifetime.

Currently, the estimated endurance of such absorbers is based on tests performed under conditions similar to those expected during actual use of the absorbers. However, their endurance is never perfectly consistent, and it depends on the user's production of CO_2, as well as the ambient temperature and pressure. Endurance estimates must be conservative to avoid a likelihood of excessive CO_2 levels in the inhaled gas. This means that some absorbing capacity usually remains in the absorber at the recommended canister change-out times.

In situations where the Submarine Rescue and Decompression System will be used, both the availability of the absorbent and the storage space are limited. Therefore, it is essential to use the absorbent completely and without allowing excess CO_2 levels in the inhaled gas.

This project was designed to develop a method to predict, on a continuous basis, the absorbent capacity remaining for each user. The project was planned to take advantage of the fact that heat is released when the CO_2 reacts with the absorbent. Indeed, such a method was developed and a patent application was filed with the U.S. Patent and Trademark office. Much like a fuel gauge in a car measures the level of gasoline, the method disclosed indicates the remaining level of absorbency. The readings are essentially independent of the ambient temperature and pressure as well as the user's ventilation and CO_2 production. The indicator can be turned on as desired, and a reading will instantly be given. It does not have to be turned at the start of absorber use to obtain recordings of previous use; therefore, it uses an absolute minimum amount of power. A prototype was built with standard analog electronics; no computer was needed. The temperature sensors that are used are stable, so calibration is not needed in the field. An additional advantage for the Navy is that the same method can be implemented for other situations in which a closed-circuit breathing apparatus is used (e.g., diving with a LAR V or a MK 16).

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INTRODUCTION

The Hyperbaric Oxygen Treatment Pack (HOTP) is a closed-circuit breathing apparatus that delivers oxygen to personnel rescued from a disabled submarine. Such a breathing apparatus minimizes consumption of oxygen and a minimum of oxygen would contaminate the chamber atmosphere.

An essential part of a closed-circuit breathing apparatus is the CO_2 absorber. This absorber removes the CO_2 that the user produces by binding it chemically, typically with some kind of sodalime. The limited working life of an absorber depends on the user's CO_2 production, level of breathing, as well as, on ambient temperature and pressure. Typically, absorbers are tested at combinations of ambient conditions likely to be seen during their actual use. Based on such results, estimates of absorber endurance can be provided to the user. However, such estimates must be conservative so that excessively high levels of CO_2 can be avoided. High levels of CO_2 can produce symptoms ranging from discomfort and headaches to loss of consciousness. By their nature, conservative estimates add to the logistical burden of providing absorbent.

Having a device and method for estimating how much absorbent capacity remains means that an absorber would have to be replaced only when its absorbent is actually used up. Thus, the amount of absorbent that has to be shipped with the Submarine Rescue and Diving Recompression System (SRDRS) can be minimized without putting the user at additional risk. The purpose of this project was to develop such a method.

METHODS

GENERAL

It is well known that the reaction between CO_2 and the chemical absorbent is exothermic. Two approaches were taken: one relied on sensing the temperature changes generated; the other relied on computer simulations to train neural networks. Obtaining temperature measurements was the primary goal and measurements of CO_2 in the scrubber outlet determined scrubber endurance.

EXPERIMENTAL DESIGN AND ANALYSIS

To simulate normal and limited control of chamber temperature, canister endurance tests were conducted at three ambient temperatures 5, 20 and 30 °C (41, 72 and 86 °F). These temperatures were combined with three depths: 0, 33 and 66 feet of seawater (fsw) i.e., 1, 2 and 3 atm abs. Two levels of ventilation were also used: 9.1 L/min, a rate close to resting ventilation and used in the initial process of selecting the HOTP; and 15 L/min, the rate often used during unmanned testing. Sodalime was used as the CO_2 absorbent, since NAVSEA guidelines required it in the initial selection process.

EQUIPMENT AND INSTRUMENTATION

To obtain temperature readings from all parts of the scrubber a total of 18 thermistors were used. This number was purposely chosen to be much larger than would be anticipated in a final design. In addition, the ambient temperature, the temperature of the inlet and outlet gas, and CO_2 level in the outlet were measured. Thermistors (model MA100GG-103, Thermometrics, Inc., Edison, NJ) were placed inside the scrubber on thin supporting threads inserted into small holes drilled through the scrubber walls. The thickest part of this thermistor is 0.080 inches (2 mm) and was deemed small enough to not disturb the gas flow in the scrubber. Each thermistor was connected to be part of a two-resistor voltage divider. Thermistor resistance could be calculated from the voltage drop across the thermistor and the value of the known resistor in the divider circuit. During setup, resistors with known resistances replaced the thermistors, and the computer's ability to correctly measure these resistances was confirmed.

The CO_2 level in the outlet was measured by continuously drawing a small gas sample (100 ml/min) to an analyzer (Ametek CD CD-3A) on the outside. All signals were connected to a computer and stored at 1 Hz. After the experiments, the manufacturer's resistance-to-temperature table (specified for every 1 °C) and linear interpolation were used to convert the recorded resistances of the thermistors to temperature readings.

A breathing simulator with CO_2 added to the expired gas was used to achieve the desired ventilation. The entire breathing apparatus was placed inside a dry container located in the B hyperbaric chamber at the Experimental Diving Facility, NEDU. The container had temperature control coils inside it. The liquid flowing through these coils was heated or cooled as needed. Several fans stirred the air inside the container and chamber pressure was adjusted to maintain the desired depth.

PROCEDURES

Before the test

The scrubber was filled with CO_2 absorbent and the HOTP unit was connected to the breathing circuit. Temperature probes were connected and their functions were verified. The ambient temperature was adjusted as desired. The CO_2 analyzer was calibrated.

Test

The chamber was pressurized to the desired depth. The data acquisition system was started. The breathing simulator, the CO_2 add and the timer on the data acquisition system were started. When the CO_2 level in the outlet reached 2% surface equivalent volume (SEV), the test and the timer were stopped.

After the test

The breathing simulator and the CO_2 add were shut off, the data acquisition was stopped, and data were backed up. The chamber was brought to the surface. Calibration gases were run through the CO_2 analyzer and readings were verified.

RESULTS

Temperature data were analyzed in several ways.

1. Certain patterns became apparent as recorded data were plotted. It was possible to generate a signal that was essentially proportional to the remaining capacity. An application to the U.S. Patent and Trademark Office (USPTO) was filed on 12 October 2001 (Navy case NC83294) to get protection for this invention. By reanalyzing the data from the recorded endurance tests, the invention was found to only be minimally affected by the ambient temperature, pressure and the user's ventilation. A prototype that only uses analog electronics was built in-house and has an indicator that shows how much CO_2 absorbency remains, much like a car's fuel gauge shows how much fuel remains in its tank. An exact description of the invention will be submitted after the USPTO decides whether to grant a patent.

2. An existing stochastic, finite element-like simulation of CO_2 absorption kinetics in a scrubber canister[1] was modified to model the HOTP canister. The previous model was of a cylindrical, axial flow canister with parallel flow across the entire canister length. The modification involved a reshaping of the absorbent canister to match the HOTP canister, and changing of the direction of flow towards the circular canister outlet. The result was a model with 270,000 volume-elements with CO_2 moving in a flow field towards the canister outlet. The HOTP model revealed that when flow rate is too high relative to the CO_2 inflow, or when canister packing is not optimal, then CO_2 may bypass the canister. However, under some conditions the exit region of the canister may heat up because bypassed CO_2 is concentrated near the HOTP outlet and its absorption probability therefore increases. This phenomenon is being further explored to see whether it can provide an early warning of premature canister breakthrough.

   Because of the canister's geometry, we initially expected that thermal profiles in the HOTP canister would be complex and that neural networks would be required to interpret them. However, both the simulated and actual profiles are relatively simple, so interpretive mathematical algorithms are not required.

DISCUSSION

A method has been found which can estimate how much absorbency remains in a CO_2 absorber. The method has been shown to be essentially independent of ambient temperature, pressure and the user's ventilation. Because of the pending patent application, details cannot be disclosed. Since the U.S. Navy is listed as the patent owner, no commercial manufacturer can charge licensing fees. An additional advantage for the Navy is that the same method can be implemented for other situations where a closed-circuit breathing apparatus is used (e.g. diving with a LAR V or a MK 16).

The prototype uses few temperature sensors to predict how much CO_2 absorbency remains. Just as a fuel gauge shows a driver how much fuel remains, a small indicator can display this information to the user, who can push a button to get an instant reading. The device does not have to be turned on at the beginning of use to record behavior of the absorber. This means that the power consumption is minimal. A prototype has been built only with analog electronics, no computer is necessary. Since temperature sensors are very stable, calibrations are rarely necessary.

This device allows prediction of how much absorbency is left in the absorber. Such information is more valuable than a CO_2 sensor monitoring the CO_2 in the inspired gas, since the CO_2 levels typically will increase only when the absorber is 80 to 90% spent. In contrast, the method and the prototype can show that the absorber has one-half or three-quarters of its capacity left. In an SRDRS scenario rescuers may be able to leave an absorber for the next group of survivors and be confident that enough absorbency remains to last those survivors through much of their decompression before absorbers are changed. Such a procedure could minimize the amount of absorbent used.

Both the simulated and actual profiles are relatively simple, so interpretive mathematical algorithms are not required. The simulation of the CO_2 absorption shows that early heating of the canister's exit region may provide an early indication of canister blow-by.

CONCLUSIONS

From temperature recordings inside the CO_2 absorber of the HOTP, a method for predicting how much absorbency remains has been developed. Using only simple analog electronics, a prototype of this method has been built.

REFERENCE

1. J. R. Clarke. "Computer Modeling of the Kinetics of CO_2 absorption in Rebreather Scrubber Canisters". In: *Oceans 2001 MTS/IEEE: An Ocean Odyssey, Conference Proceedings, Conference and Exposition, Honolulu, Hawaii, November 5-8, 2001,* Vol. 3, (Washington, DC: Marine Technology Society; Piscataway, NJ: Institute of Electrical and Electronics Engineers, 2001), pp. 1738–1744.